Decay of Tm^{173}†

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The mass assignment of Tm^{173} has been confirmed by cross bombardments involving the reactions $Er^{170}(\alpha,p)Tm^{173}$, $Yb^{173}(n,p)Tm^{173}$, and $Yb^{174}(\gamma,p)Tm^{173}$ with isotopically enriched targets, and its decay has been studied by β-ray and γ-ray scintillation spectrometry. The half-life of Tm^{173} is 8.24±0.08 h. Three gamma rays, with energies (and relative intensities) of 66 (0.01), 399 (1.0), and 465 (0.09) keV, were observed. Analysis of the β-ray spectrum indicates the presence of two major groups with end-point energies of 1.32±0.03 MeV (2%) and 0.89±0.04 MeV (98%). Gamma-gamma coincidence measurements and the γ-ray intensity data show that the 0.89-MeV β-ray group is composed of two components which differ in energy by 66 keV. The proposed decay scheme for Tm^{173} involves excited levels in Yb^{173} at 399 and 465 keV. The 399-keV level is an isomeric state with a 3.5±0.3 μsec half-life, and it de-excites by a pure $E2$ transition which is hindered by a factor of $\approx 1.6\times 10^3$ compared to the single-particle estimate. This hindrance is attributed to violation of the asymptotic selection rules for deformed nuclei.

I. INTRODUCTION

RECENTLY, Kuroyanagi and co-workers[1] observed that a (7.2±0.5)-h activity is produced by betatron irradiation of natural ytterbium. They assigned this new activity to Tm^{173} on the basis of its decay properties and the ratio of its (γ,p) yield to that of Tm^{172}. Also, a 7-h activity has been produced by fast-neutron bombardment of natural ytterbium,[2] and the yield data from these experiments again point to a Tm^{173} assignment. The radiations observed[1] to accompany the 7-h activity are a negatron group with end-point energy of 0.90 MeV and γ rays with energies of 0.40 and 0.47 MeV.

The present study was undertaken to verify the isotopic assignment of the 7-h activity and to establish its decay characteristics in more detail. By a combination of chemical separation and cross-bombardment techniques, this activity was positively identified as Tm^{173}, although the half-life (8.24 h) was found to be somewhat longer than previously reported. Study of the β and γ radiations with scintillation spectrometers has led to the formulation of a relatively simple decay scheme which involves a previously unknown isomeric state of Yb^{173}.

II. ISOTOPIC IDENTIFICATION

We have studied the activities produced in three different bombardments, each capable of yielding Tm^{173} as one of the reaction products. The gross decay rates of the various samples were measured with standard methane-flow beta proportional counters. All sources were counted for ≈4 weeks, and the experimental decay curves were analyzed into half-life components by a least-squares procedure adapted to the IBM-7090 computer.

In one of the irradiations, a 100-mg sample of Yb_2O_3 enriched[3] in Yb^{173} (95%) was bombarded for 1 h with 14.8-MeV D-T neutrons produced with the Los Alamos Cockcroft-Walton accelerator. The irradiated sample was prepared for counting by spreading it evenly over a 3-cm^2 area of an aluminum plate 0.060 in. thick. Analysis of the decay data revealed a dominant activity of half-life 8.28±0.15 h, plus others of 64 h, 4.2 days, and 32 days. On the basis of scintillation γ-ray spectra, the activities associated with the last three of the above half-lives were identified as Tm^{172}, Yb^{175}, and Yb^{169}, respectively.

In a second experiment, 100 mg of Yb_2O_3 enriched[3] in Yb^{174} (99%) were irradiated for 1 h with bremsstrahlung (23-MeV maximum energy) from the Los Alamos betatron. The irradiated sample was mounted for counting as described above. The principal activity was found to have a half-life of 8.18±0.15 h. Yb^{175} (4.2 day) was the only other activity detected. The total activity of the sample was quite low.

Finally, a 4-mg sample of Er_2O_3 enriched[3] in Er^{170} (87.5%) was bombarded with about 4 μA-h of 26-MeV α particles at the Los Alamos variable-energy cyclotron. The irradiated Er_2O_3 was dissolved in 8M HCl, and the erbium was precipitated as the hydroxide by addition of NH_4OH. This step accomplished the removal of F^{18} (111 min), formed by the reaction $O^{16}(\alpha,pn)$. The sample was then dissolved in a minimum amount of HCl, and this solution was put on a Dowex-50 resin column at 20°C. Selective elution, accomplished with 0.5M α-hydroxyisobutyric acid at pH 3.12, isolated the desired thulium activity from the other activities present in the gross sample (known contaminants: Sc^{44}, Yb^{169}, and Er^{169}). The thulium fraction was divided into two parts, each of which was evaporated to dryness on an aluminum plate. The stronger sample was used in scintillation studies. The weaker sample, used in half-life measurements, exhibited an (8.24±0.10)-h activity and a tenfold weaker activity identified as 63.7-h Tm^{172}. A trace of Tm^{170} and/or Tm^{171} was also detected.

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[1] T. Kuroyanagi, H. Yuta, K. Takahashi, and H. Morinaga, J. Phys. Soc. Japan **16**, 2393 (1961).

[2] K. Takahashi, T. Kuroyanagi, H. Yuta, K. Kotajima, K. Nagatani, and H. Morinaga, J. Phys. Soc. Japan **16**, 1664 (1961).

[3] Enriched isotopes were obtained from the Isotopes Division of the Oak Ridge National Laboratory.

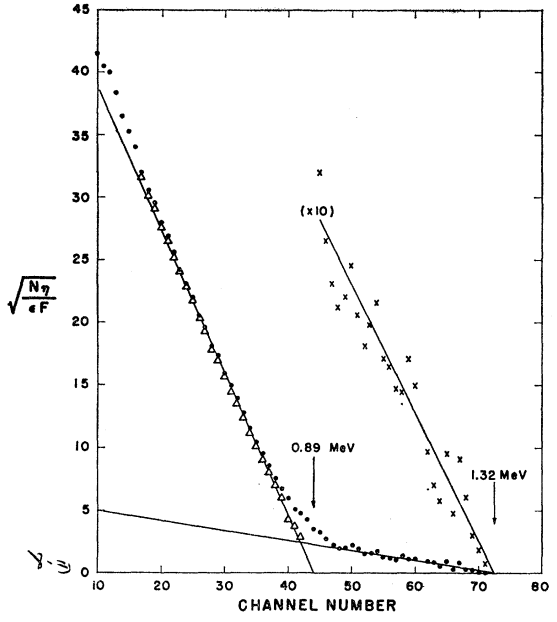

FIG. 1. Fermi-Kurie plot of the Tm^{173} beta-ray spectrum, measured with a $\frac{5}{8}$-in.$\times$1-in. trans-stilbene scintillator unit.

Based on the observed γ-ray spectra, the three 8.2-h activities formed in the above bombardments are identical. The chemical separation clearly associates this activity with an isotope of thulium. The only mass number consistent with the possible thulium product nuclei in the three bombardments is 173. The respective reactions are $Yb^{173}(n,p)Tm^{173}$, $Yb^{174}(\gamma,p)Tm^{173}$, and $Er^{170}(\alpha,p)Tm^{173}$.

III. BETA-RAY SPECTRA

The β-ray spectrum of the source produced by fast-neutron irradiation of Yb^{173} was examined with a trans-stilbene scintillator unit. The detector crystal was $\frac{5}{8}$-in. thick $\times$1-in. diam, and the source crystal distance was $\approx\frac{3}{4}$ in. The data were recorded with a fast 100-channel pulse-height analyzer (average dead time $\approx 72\,\mu$sec).

The spectrum was studied at intervals during a period of several days, and the net Tm^{173} spectrum was obtained by subtracting the time-corrected contribution of the long-lived components from the initial gross data. A Fermi-Kurie analysis of the Tm^{173} data (Fig. 1) revealed two β-ray groups with end-point energies of 1.32 ± 0.06 and 0.89 ± 0.04 MeV. The ratio of the intensity of the 1.32-MeV group to that of the 0.89-MeV group is ≈ 0.02. On the basis of γ-γ conicidence measurements and intensity-balance arguments, described below, the observed 0.89-MeV group is known to be a composite of two groups differing in energy by 66 keV.

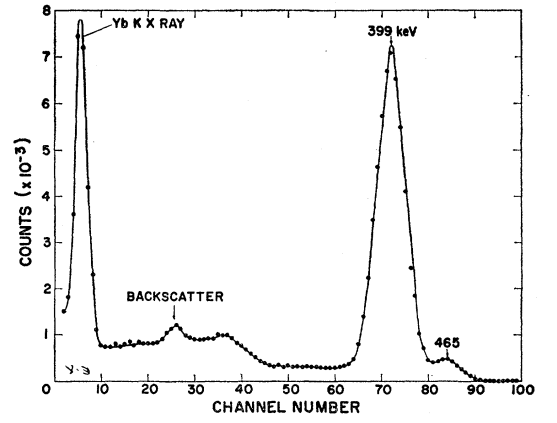

FIG. 2. Low-energy portion of the Tm^{173} gamma-ray spectrum, measured with a 2-in.$\times$2-in. NaI(Tl) crystal. Source-crystal distance=5 cm.

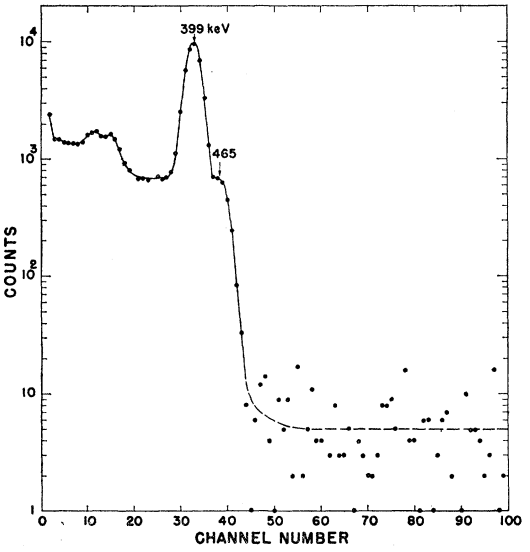

FIG. 3. High-energy portion of the Tm^{173} gamma-ray spectrum, measured with a 2-in.$\times$2-in. NaI(Tl) crystal. Source-crystal distance=1 cm.

IV. GAMMA-RAY SPECTRA

The low-energy portion (0.02–0.5 MeV) of the γ-ray spectrum associated with Tm^{173} is shown in Fig. 2. This spectrum was obtained with a 2-in.$\times$2-in. NaI(Tl) detector, a source-crystal distance of 5 cm, and with a $\frac{1}{4}$-in. Lucite plate interposed between the source and detector to absorb β rays. The source used was the irradiated Yb^{173} sample. The data of Fig. 2 represent the net contribution of Tm^{173} radiations to the initial gross spectrum; the spectral contributions of the long-lived components have been subtracted. Photopeaks are evident at 465, 399, and 53 keV, the latter resulting primarily from detection of ytterbium K x rays. Figure 3 shows the high-energy portion of the spectrum, observed with the same 2-in.$\times$2-in. crystal but with a source-crystal distance of 1 cm. From these data, we conclude that any γ ray from Tm^{173} decay having an energy >465 keV must have an intensity $\leq 2\times10^{-3}$

that of the 399-keV transition. The relative intensities of the 465-, 399-, and 53-keV photopeaks were determined to be 8.6:100:15.

From certain coincidence measurements, described in Sec. V, it became apparent that most of the K x rays result from internal conversion of a relatively strong unobserved transition. A logical guess for the energy of this "missing" transition was 66 keV (the difference between 465 and 399 keV). A careful search for 66-keV quanta was conducted with a 2-mm×30-mm NaI(Tl) detector which had a beryllium "window." A beryllium β absorber, $\frac{1}{4}$ in. thick, was interposed between the source and crystal. The source material used was the thulium fraction from the Er^{170} irradiation. Figure 4 shows the spectrum observed in the energy region below 85 keV. This spectrum was obtained from the gross data by subtracting away the underlying Compton distribution, whose intensity ($\approx 10\%$ of the x-ray peak height) was assumed to be equal to that of the flat distribution observed in the energy region 90–100 keV. The data of Fig. 4 give clear evidence for a photopeak at $\approx$66 keV. In this figure, the solid-line curve which underlies the Yb K x-ray peak is the experimental shape of the Tm K x-ray photopeak, determined from an Er^{171} spectrum recorded immediately after the Tm^{173} measurement. The solid-line curve which underlies the 66-keV position has the empirical shape of the photopeak produced by 59.6-keV γ rays from an Am^{241} source. Trial-and-error adjustment (both in pulse-height and apparent energy) of the two "standard" peaks to give the best fit to the composite peak in Fig. 4 yielded a γ-ray energy of (66±1) keV and a photon intensity ratio $I(\text{Yb } K \text{ x ray})/I(66\text{-keV } \gamma)=9.8$.

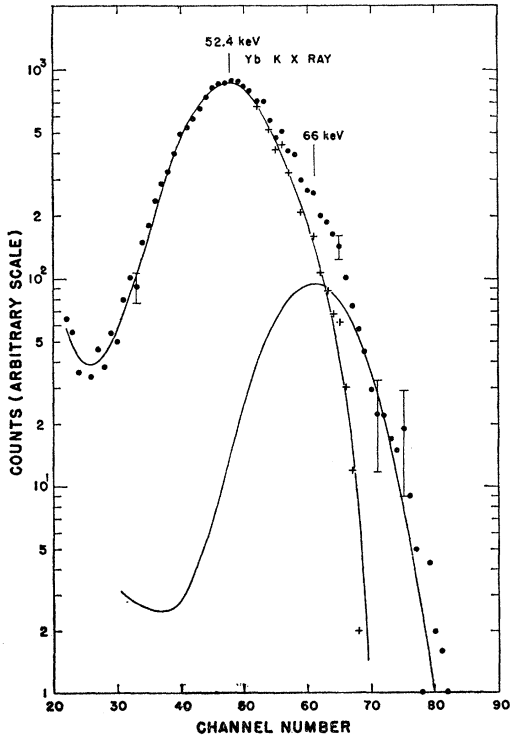

FIG. 4. X-ray region of the Tm^{173} spectrum. The detector used was a 2-mm-thick NaI(Tl) crystal with a beryllium "window."

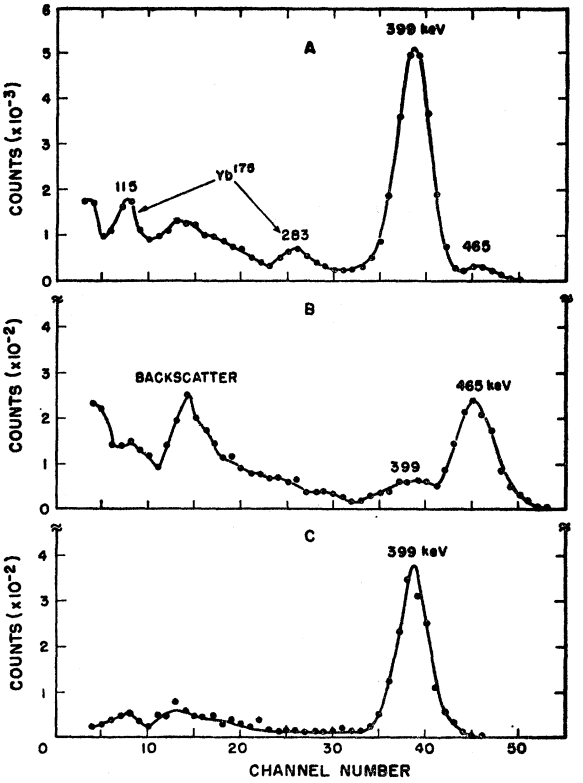

FIG. 5. Beta-gamma coincidence spectra of Tm^{173}, measured with a 2-in.×2-in. NaI(Tl) detector. Curve A shows the single-crystal spectrum, with no correction for Yb^{175} contaminant activity. Curve B shows the spectrum observed in prompt coincidence with the portion of the β-ray spectrum between 0.3 and 0.9 MeV. Curve C shows the spectrum observed in coincidence with β-ray pulses delayed 0.4 μsec.

V. COINCIDENCE MEASUREMENTS

Unless specified otherwise, all coincidence measurements were made with a "slow" coincidence spectrometer having a resolving time $2\tau=4\times10^{-7}$ sec. Pulse-height spectra were recorded with a 100-channel analyzer.

A. Beta-Gamma Coincidence Measurements

Beta-gamma coincidence experiments were performed with the 2-in.×2-in. NaI(Tl) detector and the trans-stilbene β-ray detector described above. The two scintillation crystals were positioned 0.5 in. apart, with the source between them and with a Lucite β absorber, $\frac{1}{4}$ in. thick, between the source and the γ-ray detector. The irradiated Yb^{173} sample was used as source material.

Figure 5(b) shows the γ-ray spectrum observed in prompt coincidence with those pulses produced by the portion of the β-ray spectrum between 0.3 and 0.9 MeV.

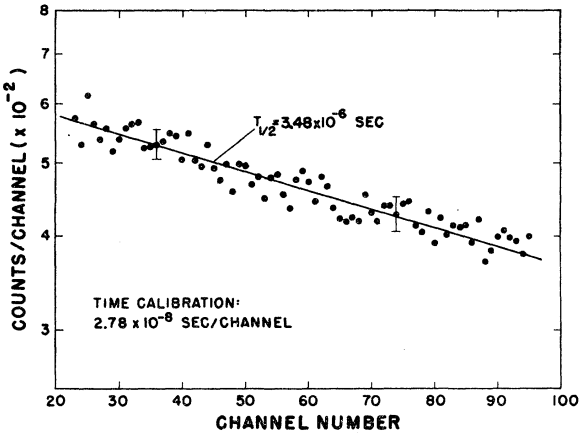

FIG. 6. Time spectrum, obtained with a time-to-pulse-height converter, of delayed coincidences between Tm^{173} beta rays and 399-keV gamma rays, showing the decay of the isomeric state in Yb^{173}.

A typical gross ungated γ-ray spectrum, with no correction for contaminant activities, is shown in Fig. 5(a) for comparison. It is apparent that the intensity of the 399-keV peak is strongly reduced (relative to that of the 465-keV peak) by the imposed β-ray coincidence condition. The simplest interpretation of this result is that the 399-keV transition originates at a delayed level. A series of β-γ delayed coincidence measurements was undertaken to explore this hypothesis. Figure 5(c) shows the γ-ray spectrum observed in coincidence with β-ray pulses delayed 0.4 μsec. The β-ray "gate" interval corresponded to the energy range 0.3–0.9 MeV. The 399-keV transition is the only γ ray observed in delayed coincidence with β rays. Examination of the delayed coincidence spectrum in the 50-keV region (not shown in the figure) revealed that only a small fraction ($\approx 15\%$) of the Yb K x rays are in delayed coincidence with β rays.

No β-γ coincidences were observed when the "window" of the β-ray coincidence channel was set to correspond to the energy range 1.05 to 1.5 MeV. It is concluded, therefore, that the observed Tm^{173} β-ray group with end-point energy 1.32 MeV corresponds to a transition to the Yb^{173} ground state.

From analysis of the delayed- and prompt-coincidence counting rates in the above experiments, it was concluded that the lifetime of the delayed state in Yb^{173} must be ≈ 4 μsec. A more accurate determination of this lifetime was obtained by a standard coincidence technique which involved measurement of β-γ delay times with a time-to-pulse-height converter. By analysis of the pulses from the time converter with a 100-channel analyzer, a large region of the "time" spectrum of coincidence events could be examined in a single run. To minimize possible interference from contaminant activities, the Tm^{173} sample isolated from α-bombarded Er^{170} was used as source material. The γ-ray detector was a $1\frac{1}{4}$-in.$\times$1-in. NaI(Tl) crystal, and the β-ray detector was a Pilot-Plastic Scintillator-B phosphor, $1\frac{3}{4}$-in. diam$\times\frac{3}{4}$ in. thick. The two detectors were oriented at 180°, about $\frac{3}{4}$ in. apart, with a $\frac{1}{4}$-in. beryllium β absorber interposed between the source and the NaI(Tl) crystal. Time calibration of the system was accomplished with a standardized electronic double pulser. Just before the Tm^{173} experiment, a sample of Er^{171}, whose decay involves a (1.05-MeV) β-(0.3-MeV)γ 2.6-μsec delayed coincidence, was studied with this apparatus. The value obtained for the half-life of the delayed state in Tm^{171} was 2.65 ± 0.15 μsec, in agreement with a previous measurement.[4] In the Tm^{173} experiment, all β-ray pulses above $\sim$100 keV were allowed to trigger the time-to-pulse-height converter. The γ-ray gate inverval was set to span the range 0.34–0.43 MeV and the coincidence time-delay interval examined was 0.5 to 3.3 μsec. Data were recorded for a total of 17 h. A semilogarithmic plot of the time spectrum obtained in the first 4-h counting period is shown in Fig. 6. A straight-line fit to the data, obtained by a least-squares analysis with an IBM 7090

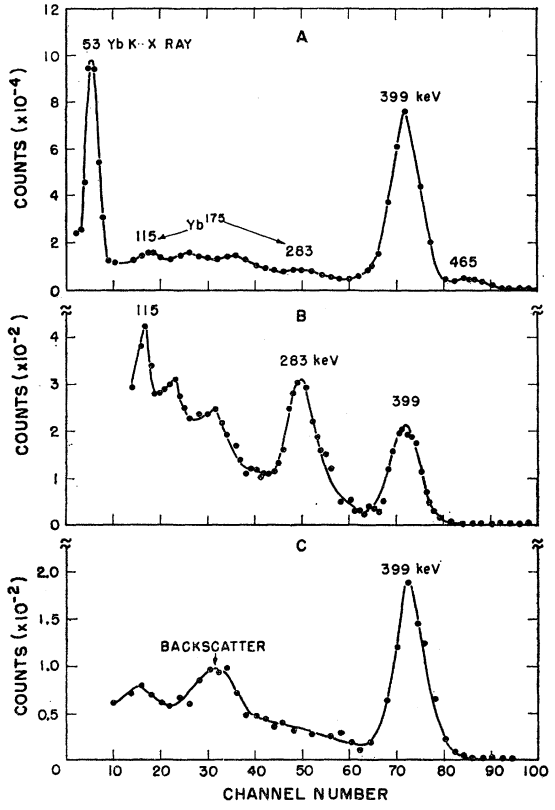

FIG. 7. Gamma-gamma coincidence spectra of Tm^{173} measured with a 2-in.$\times$2-in. NaI(Tl) crystal. Curve A shows the single-crystal spectrum, with no correction for Yb^{175} contaminant activity. Curve B shows the spectrum observed in prompt coincidence with Yb K x rays. Curve C shows the spectrum observed in coincidence with Yb K x-ray pulses delayed 0.4 μsec.

[4] F. P. Cranston, Jr., M. E. Bunker, and J. W. Starner, Phys. Rev. **110**, 1427 (1958).

gave a half-life of 3.48 μsec. Consideration of all data obtained during the 17 h indicates a half-life of 3.50 ±0.25 μsec for the isomeric state in Yb^{173}.

B. Gamma-Gamma Coincidence Measurements

The first series of γ-γ coincidence measurements was conducted with the irradiated Yb^{173} sample. In these experiments, a $1\frac{1}{2}$-in.×$1\frac{1}{2}$-in. NaI(Tl) scintillator was used as the "gate" detector and a 2-in.×2-in. NaI(Tl) crystal was used as the "analyzer" detector. The source was placed midway between the two scintillators, which were positioned ≈$\frac{3}{4}$ in. apart in a 180° orientation. Lucite plates, $\frac{1}{4}$ in. thick, served as β absorbers.

It was soon established that no two of the observed Tm^{173} γ-transitions were involved in a simple prompt-cascade relationship. The prompt coincidence spectrum observed when a narrow gate interval was centered on the 53-keV x-ray peak is shown in Fig. 7(b). For comparison, a typical gross ungated spectrum, corrected for background but uncorrected for the contribution of contaminant activities, is shown in Fig. 7(a). It is evident from spectrum *B* that essentially none of the *K* x rays are in prompt coincidence with 465-keV transitions. (*K* x ray) (399-keV γ) coincidences are observed, but from the great reduction in the intensity ratio I_γ(399 keV)/I_γ(283 keV, Yb^{175}) brought about by the imposed prompt-coincidence condition, it follows that either (a) the 399-keV transition is seldom in a cascade relationship with the transition which engenders the x rays, or (b) the (*K* x ray) (399-keV γ) coincidences involve the known isomeric state. The latter hypothesis was tested by examining the γ-ray spectrum in coincidence with *K* x-ray pulses delayed 0.4 μsec. The data obtained, shown in Fig. 7(c) not only establish that the 399-keV γ rays are in delayed coincidence with *K* x rays, but also that the γ-ray emission *follows* the x-ray emission. From analysis of the coincidence counting-rate data, it became evident that most of the observed Yb *K* x rays are in delayed coincidence with 399-keV γ rays.

A logical explanation for these observations is that the 399-keV transition is preceded by a relatively strong transition having a large *K* internal conversion coefficient–most probably the 66-keV transition observed in the ungated spectrum. In order to verify that the 66-keV γ rays do indeed populate the isomeric state, a study was made of the low-energy (<100 keV) spectrum in 0.4-μsec-delayed coincidence with pulses which contribute to the 399-keV photopeak. In this experiment, the low-energy detector was the 2-mm NaI(Tl) crystal mentioned previously, and the "gate" detector was a 1-in.×1-in. NaI(Tl) crystal. The source used was the thulium fraction separated from α-bombarded Er^{170}; the Yb^{173} sample would not have been as satisfactory because of interference from delayed coincidences associated with Yb^{169}. The delayed coincidence spectrum obtained appeared almost identical to that of Fig. 4, yielding a photon intensity ratio, I(Yb *K* x ray)/I(66-keV γ) of ≈9.

TABLE I. Coincidence relationships observed in the decay of Tm^{173} The notation (d) stands for a 3.5 μsec delayed coincidence.

Principal contributor to selected gate region	Coincident γ rays and x rays (MeV)	Coincident β-ray groups (end-point energy, MeV)
(Yb *K* x rays+0.066-MeV γ rays)	0.399 (d)	0.9
0.399-MeV γ rays	Yb *K* x rays (d) 0.066 (d)	0.9 (d)
0.465-MeV γ rays	none	0.9

All of the observed γ-γ and β-γ coincidence relationships are summarized in Table I.

VI. DISCUSSION

A. Conversion Coefficients

The *K* internal-conversion coefficients of the 66- and 399-keV transitions are determinable from the above data. In the γ-ray spectrum in delayed (0.4 μsec) coincidence with (0.3–0.9)-MeV β rays, the *K* x rays observed presumably originate entirely from internal conversion of the 399-keV transition. From the intensity ratio I(*K* x ray)/I(399-keV γ)=0.025 obtained by analysis of this spectrum, and the known ytterbium fluorescence yield, ω_K=0.937, the *K* internal-conversion coefficient of the 399-keV transition is calculated to be (2.6±0.5)×10^{-2}. Comparison of this value with the theoretical values[5] given in Table II indicates that the 399-keV transition is either predominantly *E*2 or is a mixed *E*1+*M*2 transition, with *E*1/*M*2≈11. It is concluded in the discussion below that this transition is probably pure *E*2.

TABLE II. Theoretical internal-conversion coefficients[a] for γ transitions in ytterbium.

Transition energy (keV)	Multipolarity	Internal-conversion coefficients α_K	$\Sigma\alpha_L$	$\Sigma\alpha_M$	α_T
66	*M*1	10.0	1.4	0.6	12.0
	*E*2	1.8	11.9	5.2	18.9
	*E*1	0.9	0.14	0.063	1.11
	*M*2	100	38.6	16.8	155
399	*M*1	0.064	0.009	0.003	0.076
	*E*2	0.025	0.060	0.003	0.088
	*E*1	0.008	0.0012	0.0004	0.010
	*M*2	0.22	0.041	0.016	0.27
465	*M*1	0.044	0.006	0.002	0.052
	*E*2	0.017	0.040	0.001	0.057

[a] See Ref. 5.

[5] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958).

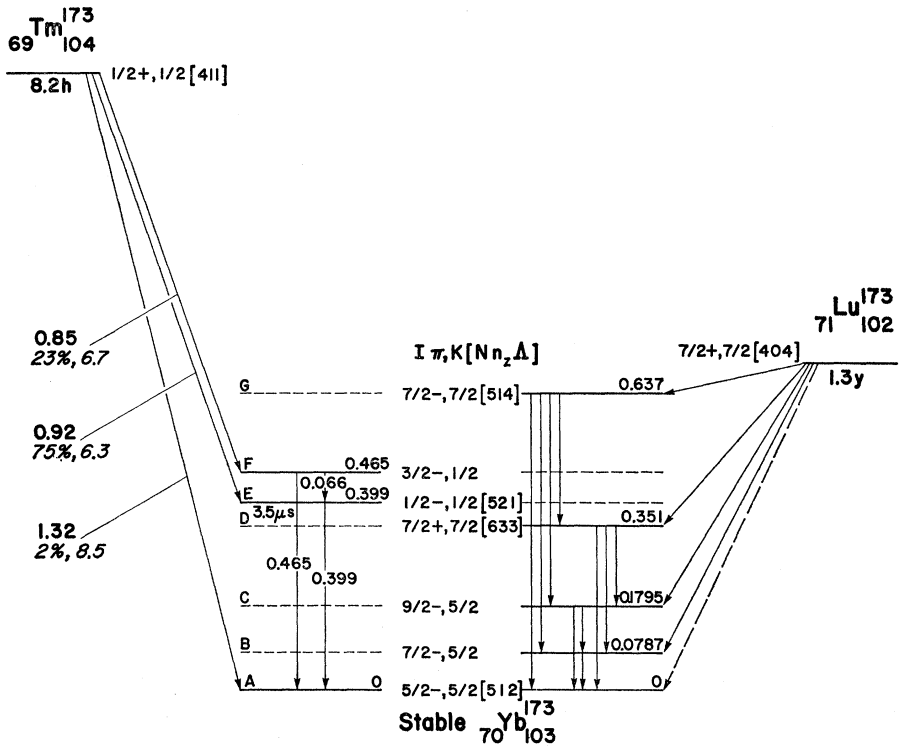

FIG. 8. Decay scheme proposed for Tm^{173}. The electron-capture decay of Lu^{173} (Ref. 10) is shown for comparison.

The Yb K x-ray peak in the γ-ray spectrum observed in delayed (0.4 μsec) coincidence with 399-keV γ rays is assumed to be entirely attributable to K-shell conversion of the 66-keV transition. Correction of the observed ratio, $I(K \text{ x ray})/I(66\text{-keV } \gamma) \approx 9$, for fluorescence yield gives a K internal-conversion coefficient of 9.5 ± 1.0 for this transition. A separate determination of α_K for the 66-keV transition is obtainable from the ungated spectrum (Fig. 2). If one assumes that the 399-keV transition is $E2$ and the 465-keV transition is $M1$, one can calculate what fraction of the K x-ray peak observed in the ungated spectrum is attributable to internal conversion of these two transitions. The remainder of the K x-ray peak is assumed to result from internal conversion of the 66-keV transition. This kind of analysis gives $\alpha_K(66 \text{ keV}) = 8.5 \pm 0.9$. The average of the above two measurements is $\alpha_K(66 \text{ keV}) = 9.0 \pm 0.7$. Comparison of this value with the theoretical values given in Table II indicates that the 66-keV transition is either predominantly $M1$ ($M1/E2 \approx 7$) or is an $E1+M2$ transition, with $E1/M2 \approx 11$.

TABLE III. Gamma-ray transitions associated with the decay of Tm^{173}.

Gamma-ray energy (keV)	Relative γ-ray intensity	Measured α_K	Assumed multipolarity	Theoretical α_T	Calculated transition intensity
66	0.012	9.0 ± 0.7	$M1/E2 \approx 7$	12.8	14
399	1.0	0.026 ± 0.005	$E2$	0.088	90
465	0.086	···	$M1$	0.057	7.6

B. Decay Scheme

The decay scheme for Tm^{173} indicated by the above results is shown in the left half of Fig. 8. The dashed lines are known levels of Yb^{173} not populated in the decay of Tm^{173}. The energies of the β transitions to levels E and F (0.92 and 0.85 MeV) were calculated by subtracting the energies of the two ground-state γ-ray transitions from the observed energy (1.32 MeV) of the β transition to the Yb^{173} ground state. The intensities of the two lower energy β-ray transitions were determined from the relative intensities of the γ-ray transitions (Table III) and the results of the Fermi-Kurie analysis, which indicate that $\approx 98\%$ of the emitted β particles are associated with a group (or groups) whose approximate end-point energy is 0.89 MeV. No attempt was made to resolve the composite 0.89-MeV β-ray group into its separate components by Fermi-Kurie analysis because the indicated separation of the two end-point energies ($\approx 8\%$) is considerably less than the inherent resolution of the β-scintillation spectrometer.

The logft values shown in Fig. 8 were determined from the Moszkowski[6] nomograms.

A summary of the γ-ray data is given in Table III.

C. Nilsson-Model Interpretation

The ground-state spin of Yb^{173} is known to be $\frac{5}{2}$. Examination of the Nilsson diagram[7] reveals that a

[6] S. A. Moszkowski, Phys. Rev. 82, 35 (1951).

nucleus with 103 neutrons should have the orbital $\frac{5}{2}-[512]$[8] as its lowest configuration; therefore, in view of the measured spin, it is assumed that this orbital corresponds to the Yb^{173} ground state. The $\frac{7}{2}-$ and $\frac{9}{2}-$ rotational states built on the ground-state configuration have been observed both in Coulomb excitation[9] and in the decay of Lu^{173}.[10] There are also electron-capture branches from Lu^{173} to levels in Yb^{173} with excitation energies of 351 and 637 keV.[10] These two states are believed to correspond, respectively, to the Nilsson orbitals $\frac{7}{2}+[633]$ and $\frac{7}{2}-[514]$.[7,10]

The fact that Tm^{173} decays to the Yb^{173} $\frac{5}{2}-$ ground state but does not decay observably to any of the known states of higher spin suggests that the spin of the parent state is $\leq\frac{3}{2}$. According to the Nilsson diagram, the ground-state configuration for $_{69}Tm^{173}$ should be $\frac{1}{2}+[411]$. This orbital satisfies the above spin restriction and in addition is the indicated assignment for the ground states of Tm^{165}, Tm^{167}, Tm^{169}, and Tm^{171}. Consequently, the Tm^{173} ground state is assumed to correspond to the Nilsson state $\frac{1}{2}+[411]$. The logft value (8.5) of the 1.32-MeV β transition is consistent with the indicated $\Delta I=2$, *yes* classification.

The logft values of the β transitions to levels E and F indicate that the asymptotic classification[7,11] for these transitions is either allowed hindered or first forbidden unhindered and that the spins of both final states are $\leq\frac{3}{2}$. The only reasonable orbital assignment for the 399-keV state is $\frac{1}{2}-[521]$, which is expected to occur as a low-lying state since in both Yb^{171} and Hf^{175} it is separated from the $\frac{5}{2}-[512]$ intrinsic state by approximately 125 keV. Since a relatively strong β transition would be expected to proceed to the $\frac{3}{2}-$ rotational state of the $\frac{1}{2}-[521]$ band, it is apparent that the 465-keV state is identifiable with this configuration. The 66-keV $(\frac{1}{2}-,\ \frac{3}{2}-)$ rotational level spacing is typical of the observed spacing in the $\frac{1}{2}-[521]$ band of other nuclei.[12]

According to the above assignments, the 399-keV γ transition is pure $E2$, which is consistent with the observed K-shell internal conversion coefficient. The lifetime of the 399-keV state is longer than the single particle estimate[13] for a 399-keV pure $E2$ transition by a factor of $\approx 1.6\times 10^3$. Presumably, this large retardation is a consequence of the fact that the asymptotic selection rules[11] forbid $E2$ transitions between two states whose quantum-number differences are $[\Delta K,\Delta N,\Delta n_z,\Delta\Lambda]=[2,0,1,1]$. Another example of a hindered $E2$ transition involving the same quantum-number differences, $[2,0,1,1]$, occurs in Ta^{181}, where the observed retardation is ≈ 400.[7]

The observed γ-ray branching from the 465-keV level leads to some interesting conclusions about the purity of this rotational state. In view of the large hindrance of the 399-keV $E2$ transition, it follows that all $E2$ transitions from the $\frac{1}{2}-[521]$ rotational band to the $\frac{5}{2}-[512]$ band must be strongly hindered. Also, $M1$ transitions between these two bands are expected to be strongly retarded because of the K selection rule, $\Delta K\leq L$. Thus, in the absence of admixed states, the 465-keV transition would not be expected to compete observably with the 66-keV rotational transition, whose lifetime is estimated to be of the order of 6×10^{-10} sec. This value is based on our calculated $M1/E2$ ratio for the 66-keV transition, the theoretical conversion coefficients of Table II, and an estimated 66-keV $E2$ γ-ray lifetime of $\tau_\gamma(E2)=7\times 10^{-8}$ sec (which corresponds to an enhancement of ≈ 75 compared to the single-particle estimate[13]). Since the 465-keV transition is 2 times weaker than the 66-keV transition, its estimated lifetime is about 1.2×10^{-9} sec. The magnitude of this lifetime strongly suggests that the 465-keV state has one or more admixed components which can proceed to the ground state via unhindered $M1$ and/or $E2$ transitions. Examination of the Nilsson diagram reveals that the most likely admixed states are $\frac{3}{2}-$, $\frac{3}{2}[512]$[14] and $\frac{3}{2}-$, $\frac{1}{2}[510]$, both of which will mix with the $\frac{3}{2}-$, $\frac{1}{2}[521]$ state through rotation-particle coupling.[15] The postulated $\frac{3}{2}[512]$ component can decay to the $\frac{5}{2}-$, $\frac{5}{2}[512]$ state via an unhindered $M1$ transition, whereas the $\frac{1}{2}[510]$ component can go to the ground state via an unhindered $E2$ transition. Since these admixed components probably have similar amplitudes, and since single-particle $M1$ transition probabilities are much higher than single-particle $E2$ transition probabilities, the 465-keV transition must be predominantly $M1$. The same reasoning suggests that the 387-keV pure $E2$ transition to level B (unobserved) should be much weaker than the 465-keV transition.

The presence of $\approx 10^{-3}$ of the $\frac{3}{2}-$, $\frac{3}{2}[512]$ state in the 465-keV state would satisfactorily account for the apparent lifetime of the 465-keV transition. Rotation-particle coupling calculations indicate that the postulated admixture could easily be as high as 10^{-3} if the $\frac{3}{2}-$, $\frac{3}{2}[512]$ state lies about 1 MeV above the 465-keV level, a spacing which would be consistent with the level systematics of this mass region. Similarly, the expected small admixture of $\frac{1}{2}-$, $\frac{1}{2}[510]$ in the 399-keV state may be largely responsible for the observed lifetime of this state, so that the actual hindrance of the transition between the $\frac{1}{2}[521]$ component and the ground state may be much higher than 1.6×10^3.

[7] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Skrifter **1**, No. 8 (1959).
[8] The symbolism used here is $K\pi[Nn_z\Lambda]$.
[9] B. Elbek, K. O. Nielsen, and M. C. Oleson, Phys. Rev. **108**, 406 (1957).
[10] J. W. Bichard, J. W. Mihelich, and B. Harmatz, Phys. Rev. **116**, 720 (1959).
[11] G. Alaga, Nucl. Phys. 4, 625 (1957).
[12] B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. **119**, 1345 (1960).
[13] S. A. Moszkowski, *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1955), p. 453.
[14] The notation used here is $I\pi$, $K[Nn_z\Lambda]$.
[15] A. K. Kerman, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **30**, No. 15 (1956).